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DESIGN CRITERIA
(ENVIRONMENT)

MODELS OF VENUS ATMOSPHERE (1968)

December 1968

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FOREWORD

NASA experience has indicated a need for uniform criteria for the design of space vehicles. Accordingly, criteria are being developed in the following areas of technology:

Environment
Structures
Guidance and Control
Chemical Propulsion

Individual components of this work will be issued as separate monographs as soon as they are completed. This document, Models of Venus Atmosphere (1968), is one such monograph. A list of all monographs in this series issued prior to this one can be found on the last page of this document.

These monographs are to be regarded as guides to design and not as NASA requirements, except as may be specified in formal project specifications. It is expected, however, that the criteria sections of these documents, revised as experience may indicate to be desirable, eventually will become uniform design requirements for NASA space vehicles.

This monograph was prepared under the cognizance of the Goddard Space Flight Center with Scott A. Mills as Program Coordinator. The principal authors were Robert A. Schiffer and Andrew J. Beck of the Jet Propulsion Laboratory. Dr. M. B. McElroy of Kitt Peak National Observatory served as consultant for portions of this monograph. The comments of scientists and engineers participating in the review cycle were helpful and appreciated.

Comments concerning the technical contents of these monographs will be welcomed by the National Aeronautics and Space Administration, Office of Advanced Research and Technology (Code RVA), Washington, D. C. 20546.

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CONTENTS

MODELS OF VENUS ATMOSPHERE (1968)

1. INTRODUCTION

Design and mission planning for space vehicles which are to orbit or land on Venus require quantitative data on its atmosphere. However, a clear understanding of the Venus atmosphere awaits additional scientific measurements and theoretical studies. To serve design and planning requirements until more definitive knowledge evolves, this monograph provides a set of engineering models of the Venus atmosphere, based on theory and data available in August 1968.

In preparing these models, an assessment was made of the effects which planetary atmospheric characteristics might have on the performance of the space vehicle and its major subsystems. These characteristics include the structure, composition, and dynamics of the atmosphere, which can have both aerodynamic and thermal effects on the space vehicle. Table I lists major vehicle subsystems and shows the atmospheric parameters affecting each subsystem.

Of these atmospheric variables, the vertical distribution of mass density is regarded as the most critical parameter for design functions which involve aerodynamic effects. However, chemical composition and temperature structure also require definition because they affect density and thermal calculations. In addition, the viscosity, specific heats, and speed of sound influence vehicle aerothermodynamic analyses; and atmospheric winds affect entry dynamics for terminal descent. Finally, the atmospheric aerosol content and opacity constrain the design of landed solar power systems and influence performance of communications equipment.

The six engineering models developed for this monograph include low and high density models for each of three periods of solar activity (minimum, mean, and maximum). For each model, profiles of density, pressure, temperature, molecular mass, and other parameters are given.

2. STATE-OF-THE-ART

2.1 Atmosphere

Prior to 1967 no in situ measurements had been made of the Venus atmosphere. Physical descriptions of the thermodynamic and chemical processes were based on individual interpretations of remotely-obtained data. The consequent variation in interpretation resulted in formulation of widely differing atmospheric models such as given in References 1, 2, 3, 4, and 5. An analysis of these models reveals wide ranges in surface pressure,

TABLE I

SPACE VEHICLE SUBSYSTEMS AND PERTINENT ATMOSPHERIC PARAMETERS

SPACE VEHICLE SUBSYSTEMS	ATMOSPHERIC PARAMETERS								
	Pressure	Temperature	Density	Specific Heat	Viscosity	Speed of Sound	Composition	Winds	Opacity and Aerosols
STRUCTURAL			X	X	X	X		X	
RETARDATION			X	X	X	X	X	X	
PROPULSION	X	X	X	X	X	X	X	X	X
HEAT SHIELD			X	X	X	X	X		
GUIDANCE	X	X	X			X		X	
ATTITUDE CONTROL	X	X	X			X		X	
COMMUNICATIONS	X		X				X		X
POWER SUPPLY	X	X	X				X	X	X
ELECTRONICS	X	X	X				X		
MECHANICAL DEVICES	X	X	X					X	X
THERMAL CONTROL	X	X	X	X	X		X	X	X

composition, and temperature; and also shows differing interpretations of the relationship between the temperature structure and observed planetary radiation.

The recent Mariner V and USSR Venera 4 measurements have permitted improvement upon earlier atmospheric models by providing data which have narrowed substantially the ranges of uncertainty for composition and temperature structure. On the other hand, analysis of the data from these two probes has resulted in uncertainties in values of the planet's radius, surface pressure, and surface temperature.

2.1.1 Surface Pressure

Thus far, the only direct measurement of atmospheric parameters on Venus has resulted from the USSR Venera 4 entry probe which penetrated the dark hemisphere atmosphere near the equator some 1500 ± 500 km from the dawn terminator.*

The reported surface pressure ranged from 16.4 to 20.3 (Earth) atmospheres (ref. 6). During descent, vehicle local altitude was referenced at 26 km by a marking radar altimeter. However, the planetary surface radius at the reported landing location was not measured, thus resulting in uncertainty as to whether these pressures are surface values, reflect some topographical feature, or represent some level above the surface (because of possible altimetry error).

Radio transmission from Mariner V during the occultation experiment did not penetrate the Venus atmosphere to the surface because of high gas refractivity. Kliore (ref. 7) reported that "critical refraction" was reached at about 5 atmospheres. At this pressure excessive bending of the radio waves prevented further spacecraft-Earth communications until the spacecraft emerged at the other side of Venus. The Mariner V trajectory was referenced to the gravitational center of the planet. A superposition of the Mariner V and Venera 4 temperature and pressure data interpretations (refs. 6 and 8) results in profiles which agree remarkably well (figs. 1 and 2) if the planetary radius at the Venera 4 final data transmission point is taken as approximately 6078 km.

The radar determination of the Venus radius, reported by Ash, Shapiro, and Smith as 6056 ± 1.5 km (ref. 9), later was revised by Ash et al.to 6050 ± 0.5 km (ref. 10). The uncertainty quoted is the formal standard error; a realistic estimate of the uncertainty is probably closer to 5 km. Mariner V ranging data combined with simultaneous radar data, reported by Anderson et al. (ref. 11), give a radius of 6056± 2.1 km. The lowest radar radius of approximately 6048 km, reported in Reference 10, is taken in this monograph as the surface defining the upper value of surface pressure. It is doubtful that the discrepancy in radius values between Venera 4 and radar results can be attributed to topographical features.

The resolution of an appropriate uncertainty range for the mean surface pressure is a direct consequence of the uncertainty in the planetary mean surface radius. The surface pressure, based on the Venera 4 data, could be as high as 167 atmospheres if the selected minimum value for the planetary radius is approximately correct and the Venera 4 probe did not, in fact, impact at the instant of final data transmission. The value of 167 atmospheres results from a downward adiabatic extrapolation of the Venera 4 pressure data to a surface at a 6048 km radius (fig. 1). If there are clouds of water or any other condensate, the vertical temperature gradient would be limited by the convective processes to an appropriate saturated adiabatic rate of change of temperature with height. However, the dry adiabatic

*As reported in PRAVDA release of October 22, 1967.

temperature gradient is used here since it allows for a more conservative (higher) estimate of the maximum surface pressure and temperature.

The lower limit surface pressure of 16.4 atmospheres for the models in this monograph corresponds to the minimum of the Venera 4 pressure values at the 6078 km radius. Although Reference 12 argues that the Soviet probe did indeed transmit data up to impacting on the surface, the lower surface (at the radius determined by radar) seems more reasonable. Available data, however, do not yet justify resolution of the divergency in radius values.

2.1.2 Composition

Carbon dioxide is the only major component gas positively identified by spectroscopic study of the Venus atmosphere (refs. 13 and 14). Venera 4 gas analyzers likewise indicated near 90% CO_2 during terminal descent (ref. 15). Kliore (ref. 7) also proposes a high percent of CO_2 (75-90%) in his interpretation of the Mariner V occultation data. For another major gas in the Venus atmosphere scientists generally have proposed nitrogen although it has not been detected spectroscopically or by other means. The two Venera 4 gas analyzers with threshold levels of 7% and 2.5% similarly did not register its presence. However, Kliore (ref. 8) has obtained a good fit to the Mariner V occultation data with models having up to 25% nitrogen. There is believed to be insufficient evidence for elimination of nitrogen as a minor gas component.

Spectroscopic observations have detected water vapor (refs. 16, 17, and 18) and have placed an upper limit on the abundance of molecular oxygen (ref. 19). Venera 4 measurements have implied much greater proportions for both of these gases (ref. 15).

A cloud composition of ice would tend to resolve the apparent contradiction in water abundance between spectroscopy and Venera 4 results. In the case of ice clouds, spectroscopic observations (confined to the region above the clouds) would show the atmosphere to be relatively dry while the Venera 4 probe into the lower atmosphere would show significantly more moisture. However, there is no apparent explanation for the different proportions of molecular oxygen shown by spectroscopy and Venera 4, respectively. The weight of evidence suggests that the spectroscopic studies are more reliable so the upper limit on the percentage of oxygen by volume indicated by spectroscopy is considered to prevail throughout the atmosphere.

Interpretation of Mariner V photometric data by Barth et al. (ref. 20) proposed the presence of both molecular and atomic hydrogen in the extreme upper atmosphere of Venus. Reference 21 proposes deuterium. Other observed constituent gases include hydrogen fluoride and hydrogen chloride (ref. 22), and carbon monoxide (ref. 23).

Table II summarizes current estimates of percentages by volume of component gases in the Venus atmosphere. Since the total of estimated percentages of identified gases does not reach 100% (unless the higher part of the estimated CO_2 range is used), the presence of unidentified gas is considered likely. It is estimated that about 2.5% of the carbon dioxide in the Venus upper atmosphere could be dissociated and still be consistent with the ionospheric scale heights observed by Mariner V.

It was concluded that for this monograph the low density models should be almost pure CO_2 with no dissociation and the high density models should be 10% N_2 and 90% CO_2 with

TABLE II

COMPOSITION OF THE VENUS ATMOSPHERE*

Component	Estimated Percent by Volume	Source
CO_2	90 ± 10	Vinogradov
N_2	<7	"
NH_3	$<5\times10^{-6}$	Benedict
N_2O	$<5\times10^{-5}$	"
CO	$\simeq 4.5\times10^{-3}$	"
H_2O	$>5\times10^{-2}$ and $<7\times10^{-1}$	Vinogradov
O_2	$\simeq 3\times10^{-3}$	Hunten
HCl	$\simeq 10^{-4}$	Benedict
HF	$\simeq 10^{-6}$	"
He	$\simeq 10^{-2}$	McElroy
CH_4	$<7\times10^{-5}$	Kuiper
COS	$<5\times10^{-5}$	"

*Summarized from Proceedings of Second Arizona Conference on Planetary Atmospheres, Tucson, March 11-13, 1968, in Journal of Atmospheric Sciences, Vol. 25, No. 4, July 1968.

2.5% CO_2 dissociation above the turbopause. Both low and high density models have traces of hydrogen and helium; other observed gases are omitted since they would have negligible effect on the mass density structure.

2.1.3 Temperature

Independent measurements of temperatures for both the planetary surface and the atmosphere were synthesized to construct vertical temperature models. Figure 2 shows the temperature data for the atmosphere which were used.

Microwave observations of Venus have provided a measure of the spectra of brightness temperature (radiation intensity) over a wide range of Sun-Venus-Earth angles (refs. 24-26). The variation of these spectra with the Venus-Sun-Earth angle is known as the microwave phase effect. The surface temperatures have been derived by assuming radio emissions of centimeter wavelength to be of thermal origin with a surface emissivity of about 0.9. Interpretation of the microwave phase effect can give surface temperatures from 470°K to a high extreme of 1000°K over the full range of phase angles.

On the other hand, there are strong arguments for the concept of a near isothermal surface. The thermal inertia of a deep atmosphere theoretically is too great for the temperature to respond strongly to diurnal changes on Venus (the Venus day is about 116.8 Earth days). For a surface pressure of 15 atmospheres, surface temperature of 500°K, and the mean solar flux at Venus, the thermal inertia at the surface would be too great for the temperature to be affected by the alternation of night and day associated with the Venus rotation rate. For higher surface pressures, the thermal inertia would be greater. Any diurnal changes are most likely to occur well away from the surface.

Time dependent calculations have confirmed that there is almost no diurnal variation of temperature in the lower atmosphere of Venus. The calculations for such a deep atmosphere show that surface and atmosphere are thermally coupled so strongly that only a negligible boundary layer can develop. Convective-radiative model solutions lead to the conclusion that there should be no diurnal variations of surface temperature and therefore no microwave phase effect. The virtually identical temperature profiles obtained during immersion (dark side) and emersion (sunlit side) by the Mariner V occultation experiment also give no indication of diurnal changes. There is at present no thermal model of the Venus lower atmosphere which is compatible with a phase effect. Consequently, an isothermal surface was used for all atmospheric models presented herein.

Observation of a temperature gradient of about 9.5°K per km in a 26 km atmospheric layer below the cloud tops by the Venera 4 probe provided evidence for a convective troposphere with a near adiabatic lapse rate. This result agrees reasonably well with the adiabat for a predominantly carbon dioxide atmosphere at the Venus ambient temperatures and pressures. The Venera 4 temperature data were referenced to a planetary surface at the 6078 km radius as discussed in 2.1.1. Use of this surface provides reasonable continuity with the Mariner V temperature profile for the immersion phase of the occultation experiment (fig. 2).

Cloud temperatures measured by Earth based infrared radiometers (ref. 27) and by Mariner II (ref. 28) range from 220° to 250°K for both the sunlit and dark hemispheres. The cloud top elevation is taken at a radius of 6120 ± 7.5 km, based on optical observation. These

cloud temperatures are consistent with interpretations based on the refractivity gradient observed during the Mariner V occultation experiment (refs. 7 and 8). Observed decreases of infrared intensity at the edges of Venus (limb darkening) have been interpreted to be the consequence of a small temperature lapse rate with altitude (about 2° to 3°K/km) in and above the cloud top region.

The temperature models presented in this monograph are derived from the Mariner V and Venera 4 measurements and interpretations and also from McElroy's theoretical atmospheric thermal model (ref. 29). Venus exospheric temperatures for periods of minimum, mean, and maximum solar activity have been calculated by McElroy on the basis of observed ultraviolet solar flux-Earth exospheric temperature statistics. Table III shows the relative magnitude of the solar ultraviolet flux (below 1000 angstroms) at the Venus solar distance and the estimated exospheric temperatures for minimum, mean, and maximum solar activity.

TABLE III

VARIATION OF UV FLUX* AND EXOSPHERIC TEMPERATURE WITH SOLAR ACTIVITY

Solar Activity	Ratio of UV Flux to Solar Min UV Flux	Exospheric Temperature (°K)
Minimum	1.0	625±187
Mean	1.5	710±213
Maximum	3.0	931±279

*Below 1000 angstrom wavelength

The minimum and maximum solar activity levels in Table III represent estimated nominal values which describe the fluctuations observed during the last solar cycle. The mean model is representative of the solar activity level at the time of the Mariner V Venus flyby on October 19, 1967. However, the prediction of future solar fluxes can be performed only in a statistical manner and would result in additional uncertainty.

2.1.4 Molecular Mass

The variation of molecular mass with altitude in a planetary atmosphere is affected by the mutual interaction of photochemistry, gravity, and dynamics. Because of limited understanding of the relative importance of these physical processes in the Venus atmosphere, a simplified treatment of the problem is used in which the mean molecular mass is assumed constant up to the turbopause altitude. The turbopause is the altitude below which the atmospheric gases mix in constant proportions; above this altitude each constituent gas is taken to be in diffusive equilibrium, with number density decreasing with altitude at a rate which is dependent upon its individual molecular mass and the ambient atmospheric

temperature. The turbopause altitude on Venus is assumed analogous to that of Earth. In the terrestrial atmosphere the turbopause is observed at an altitude of approximately 120 km where the mass density is approximately 2.4×10^{-11} gm/cm^3 and number density is 5.2×10^{11} cm^{-3} (ref. 30). For the Venus models of this monograph, the turbopause is chosen at the altitudes having this number density, which corresponds to a mass density of 3.52×10^{-11} or 3.65×10^{-11} gm/cm^3, depending upon composition. For convenience a value of 3.6×10^{-11} gm/cm^3 has been selected for all models presented herein.

2.1.5 Gravity

The acceleration of gravity g_o at the surface of Venus* is derived from the Venus gravitational constant of $GM_♀ = 324{,}859.6 \pm .5$ km^3/sec^2 measured by Mariner V (ref. 31). The models presented in this monograph account for the variation of gravitational acceleration with altitude.

2.1.6 Winds

Because the opaque cloud layer prevents direct observation of the Venus atmosphere, circulation must be inferred primarily from theory. Recent radiometric and radar measurements in the microwave region of the spectrum have provided information about the planetary surface temperatures and rotation rate (refs. 9 and 26). Both of these parameters have a direct bearing on the basic atmospheric circulation. A strict Earth circulation analogy is not valid since the Coriolis parameter is much smaller for Venus.† Consequently, in contrast to the Earth where zonal (east-west) flow prevails, the Venus circulation should be dominated by a flow component along the great circles joining the subsolar and antisolar points (ref. 24).

Simplified hydrodynamic analyses of the Venus wind structure are presented in Reference 32. These theoretical studies predict average wind speeds of 2 to 8 m/sec. Another circulation model proposed by Goody and Robinson (ref. 33) predicts wind speeds on the order of 18–30 m/sec. If such high velocities do prevail on Venus, topographical features such as mountains certainly will influence the wind near the surface. Recently, Boyer and Newell (ref. 34) proposed atmospheric velocities as high as 100 m/sec to explain cloud feature motions shown by ultraviolet photographs.

In view of the limited data and wide range of values, the wind studies to date should be considered preliminary and used with caution. A satisfactory understanding of the Venus wind system must await new data and/or a circulation analysis which includes atmospheric radiative and convective processes.

2.1.7 Clouds

A pale yellow opaque cloud veil with a spherical (Bond) albedo of approximately 0.71 prevents visual observation of the Venus surface. Reference 24 summarizes current

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* $g_o = \frac{GM_♀}{r_o^2}$, where r_o is the planetary surface radius

† The Coriolis parameter is proportional to the planetary rotation rate, and Venus rotates once in approximately 243 Earth days.

knowledge and discusses models which have been proposed to interpret the structure and composition of the Venus cloud system.

It is not known whether the clouds consist of a single layer or are stratified, with differing compositions, temperatures, and radiation emission spectra. The multiple layer concept is proposed to explain the observed variations of emission with wavelength. One prominent characteristic is the relative insensitivity of the cloud temperature (220° to 250°K) to diurnal changes of incoming solar radiation. Scientists have proposed various substances as cloud material including water, ammonium nitride, ammonium chloride, hydrocarbonamide type polymers, carbon suboxide, formaldehyde, nitrogen dioxide, and dust. Ohring et al. (ref. 32) have calculated cloud opacities consistent with the often proposed atmospheric green-house effect. Their conclusions have weakened the argument for the necessity for an appreciable amount of water in the atmosphere. The nature and composition of the Venus clouds remain subjects of conjecture in the absence of additional data.

2.2 Choice of Model Parameters

Table IV shows the input parameters for the six engineering models of the Venus atmosphere that have been developed. Models V-1 and V-2 have exospheric temperatures corresponding to minimum solar activity; exospheric temperatures for Models V-3 and V-4 are for mean solar activity; and exospheric temperatures for Models V-5 and V-6 are for maximum solar activity. Models V-1, V-3, and V-5 are high density models characterized by high pressure and low molecular mass. Models V-2, V-4, and V-6 are low density models characterized by low pressure and high molecular mass.

The two chemical compositions chosen for the high and low density models, respectively, allow for a molecular mass range which is consistent with current estimates of atmospheric content as given in 2.1.2.

Ranges in surface pressures and temperature contained in the six models result in part from uncertainty in the mean planetary radius. Accordingly, the lower pressure and temperature limits given in these models are the values for a planetary radius of 6078 km, and the upper pressure and temperature limits are the values for a planetary radius of 6048 km (fig. 1). The temperature structure is based on McElroy's thermal model (ref. 29). Figure 3 shows the vertical temperature profiles used herein.

2.3 Calculation

The models presented in this monograph were generated by the computer program described in Reference 35. The program was modified to include a molecular mass subroutine (based on the molecular mass variation with altitude discussed in Paragraph 2.1.4), an extended temperature range for the calculation of the specific heat and the reduced collision integral $\Omega^{(2,2)*}$ which appears in the viscosity relationship (as shown in Appendix B), an extended pressure range for the calculation of the specific heat (based on the data of References 36 and 37), and thermochemical data which allow for the inclusion of atomic oxygen as a component gas.

The basic inputs to the computer program are the temperature profile, the surface pressure, the near surface atmospheric composition and corresponding molecular mass, the planetary

TABLE IV

COMPUTER INPUTS FOR MODELS OF VENUS ATMOSPHERE (1968)

PARAMETERS	Minimum Solar Activity		Mean Solar Activity		Maximum Solar Activity	
	High Density (Model V-1)	Low Density (Model V-2)	High Density (Model V-3)	Low Density (Model V-4)	High Density (Model V-5)	Low Density (Model V-6)
Planetary Radius (km)	6048	6078	6048	6078	6048	6078
Surface Gravity (cm/sec^2)	888.1	879.4	888.1	879.4	888.1	879.4
Surface Pressure (atm)	167	16.4	167	16.4	167	16.4
Surface Temperature (°K)	770	534	770	534	770	534
Exospheric Temperature (°K)	625	625	710	710	931	931
Below the Turbopause						
1. Composition (percent by volume)						
N_2	10		10		10	
CO_2	90	100	90	100	90	100
2. Molecular Mass (grams/gram-mole)	42.4	44.0	42.4	44.0	42.4	44.0
At the Turbopause						
1. Composition (percent by volume)						
N_2	10		10		10	
CO_2	87.73	99.98	87.73	99.98	87.73	99.98
CO	1.125		1.125		1.125	
O	1.125		1.125		1.125	
He	0.01	0.01	0.01	0.01	0.01	0.01
H_2	0.01	0.01	0.01	0.01	0.01	0.01
2. Molecular Mass (grams/gram-mole)	41.9	44.0	41.9	44.0	41.9	44.0
3. Density ($grams/cm^3$)	3.6×10^{-11}	3.6×10^{-11}	3.6×10^{-11}	3.6×10^{-11}	3.6×10^{-11}	3.6×10^{-11}

radius, the acceleration of gravity at the planet's surface, and the atmospheric density at the turbopause. The values for density, pressure, speed of sound, molecular mass, density scale height, number density, mean free path, and viscosity as functions of altitude are calculated, using the mathematical relationships given in Appendix B plus those required to determine the mean molecular mass values above the turbopause in accordance with 2.1.4. These relationships satisfy the hydrostatic equation and equation of state. Table IV shows the input parameters to the computer program for the models presented in this monograph.

3. CRITERIA

For orbiter and entry analyses and for related space vehicle design, the engineering models of the Venus atmosphere presented herein should be used. The models should be regarded as approximations which encompass current uncertainties in atmospheric parameters.

The bimodal nature of the data was appropriate for development of low and high density models but does not justify a mean density model. The low density models were derived from the higher value of the radius (defined by superposition of the Mariner V and Venera 4 temperature and pressure interpretations). The high density models were based on the lower value of the radius (derived from radar measurements). The likelihood of the planetary radius being near the center of the range of radius values appears remote; consequently, no mean models were developed.

3.1 Atmospheric Models

Tables V through X give six engineering models of the Venus atmosphere; the calculated density profiles for these models are shown in Figure 4.

Tables V and VI (Models V-1 and V-2) should be applied to Venus missions at times of minimum solar activity; Tables VII and VIII (Models V-3 and V-4) should be applied during moderate solar activity; and Tables IX and X (Models V-5 and V-6) during maximum solar activity.

Calculations and listing of all quantities for these six tables were arbitrarily terminated at altitudes where the density falls to 10^{-16} gm/cm^3 since the hydrostatic equilibrium assumption upon which these models are based undoubtedly becomes invalid at greater altitudes.

3.2 Winds

Uncertainties in knowledge of the dynamics of the Venus atmosphere preclude the specification of a realistic wind model at this time. However, for interim design purposes the following model is suggested:

Mean horizontal wind speed:	2 - 30 m/sec
Mean horizontal wind speeds at cloud altitudes:	100 m/sec
Maximum wind shear:	0.05 m/sec/m

3.3 Clouds

No acceptable model describing the cloud composition, aerosol content, or opacity of the Venus atmosphere is available.

TABLE V*

1968 VENUS MODEL ATMOSPHERE, V-1

(HIGH DENSITY AND MINIMUM SOLAR ACTIVITY)

Geometric Altitude (km)	Temp (°K)	Pressure (mb)	Density (gm/cc)	Speed of Sound (m/sec)	Molecular Mass (grams/gram-mole)	Density Scale Height (km)	Number Density (per cc)	Mean Free Path (m)	Viscosity (kg/m sec)
0	770.0	1.69+05	1.12-01	412	42.4	20.29	1.59+21	9.18-10	3.26-05
5	733.3	1.25+05	8.71-02	411	42.4	19.35	1.24+21	1.18-09	3.16-05
10	696.6	9.13+04	6.68-02	405	42.4	18.42	9.49+20	1.54-09	3.05-05
15	660.0	6.54+04	5.06-02	395	42.4	17.48	7.18+20	2.03-09	2.93-05
20	619.9	4.60+04	3.79-02	384	42.4	16.76	5.38+20	2.72-09	2.79-05
25	579.9	3.16+04	2.78-02	372	42.4	15.71	3.95+20	3.70-09	2.65-05
30	540.0	2.12+04	2.00-02	360	42.4	14.65	2.84+20	5.14-09	2.52-05
35	494.1	1.37+04	1.42-02	346	42.4	13.88	2.01+20	7.26-09	2.36-05
40	448.3	8.54+03	9.72-03	331	42.4	12.62	1.38+20	1.06-08	2.17-05
45	402.6	5.05+03	6.40-03	315	42.4	11.35	9.09+19	1.61-08	1.98-05
50	357.0	2.81+03	4.01-03	298	42.4	10.08	5.70+19	2.57-08	1.76-05
55	311.4	1.44+03	2.36-03	280	42.4	8.81	3.35+19	4.36-08	1.56-05
60	273.3	6.68+02	1.25-03	264	42.4	6.40	1.77+19	8.26-08	1.37-05
65	265.0	2.93+02	5.64-04	261	42.4	6.21	8.01+18	1.83-07	1.33-05
70	255.8	1.25+02	2.50-04	257	42.4	6.09	3.55+18	4.12-07	1.29-05
75	244.1	5.18+01	1.08-04	252	42.4	5.87	1.54+18	9.52-07	1.23-05
80	231.1	2.04+01	4.51-05	246	42.4	5.56	6.40+17	2.28-06	1.18-05
85	218.8	7.66+00	1.79-05	241	42.4	5.23	2.54+17	5.76-06	1.12-05
90	207.9	2.73+00	6.70-06	235	42.4	4.97	9.52+16	1.54-05	1.07-05
95	196.8	9.23-01	2.39-06	198	42.4	4.74	3.40+16	4.30-05	1.02-05
100	185.7	2.93-01	8.04-07	192	42.4	4.45	1.14+16	1.28-04	0.94-05
110	171.1	2.47-02	7.37-08	184	42.4	3.99	1.05+15	1.40-03	0.85-05
120	203.3	2.23-03	5.60-09	232	42.4	4.17	7.97+13	1.84-02	1.05-05
130	214.8	2.85-04	6.76-10	238	42.4	4.88	9.60+12	1.52-01	1.10-05
140	265.8	4.37-05	8.38-11	265	42.4	5.22	1.19+12	1.23+00	1.34-05
150	366.6	1.08-05	1.50-11	313	42.4	6.70	2.14+11	6.83+00	1.81-05
160	471.9	3.94-06	4.15-12	346	42.4	9.31	6.05+10	2.41+01	2.26-05
170	542.9	1.72-06	1.59-12	369	41.8	11.67	2.29+10	6.44+01	2.53-05
180	583.8	8.16-07	6.92-13	386	41.2	12.87	1.01+10	1.46+02	2.67-05
190	602.9	4.09-07	3.29-13	391	40.3	13.78	4.92+09	3.00+02	2.73-05
200	612.7	2.12-07	1.64-13	399	39.3	14.65	2.51+09	5.87+02	2.76-05
210	617.9	1.13-07	8.40-14	407	38.0	15.30	1.33+09	1.11+03	2.78-05
220	620.4	6.23-08	4.41-14	416	36.5	15.87	7.27+08	2.03+03	2.79-05
230	621.3	3.52-08	2.37-14	426	34.9	16.44	4.10+08	3.59+03	2.79-05
240	621.5	2.05-08	1.31-14	438	33.0	17.15	2.39+08	6.17+03	2.79-05
250	621.7	1.23-08	7.39-15	452	31.0	17.96	1.44+08	1.03+04	2.79-05
260	621.8	7.68-09	4.29-15	468	28.9	18.92	8.98+07	1.65+04	2.79-05
270	622.0	4.95-09	2.57-15	486	26.8	20.05	5.77+07	2.56+04	2.79-05
280	622.1	3.30-09	1.58-15	596	24.8	21.33	3.84+07	3.83+04	2.79-05
290	622.3	2.27-09	1.00-15	527	22.8	22.75	2.65+07	5.57+04	2.80-05
300	622.4	1.62-09	6.56-16	550	21.0	24.30	1.88+07	7.84+04	2.80-05
310	622.6	1.18-09	4.40-16	574	19.3	25.95	1.37+07	1.07+05	2.80-05
320	622.7	8.87-10	3.03-16	599	17.7	27.68	1.03+07	1.43+05	2.80-05
330	622.9	6.83-10	2.13-16	627	16.2	29.46	7.95+06	1.85+05	2.80-05
340	623.0	5.39-10	1.53-16	656	14.8	31.30	6.26+06	2.35+05	2.80-05
350	623.1	4.34-10	1.12-16	688	13.4	33.20	5.05+06	2.92+05	2.80-05
360	623.3	3.57-10	8.39-17	722	12.2	35.16	4.15+06	3.55+05	2.80-05

*A one- or two-digit number (preceded by a plus or minus sign) following an entry indicates the power of ten by which that entry should be multiplied.

TABLE VI*

1968 VENUS MODEL ATMOSPHERE, V-2

(LOW DENSITY AND MINIMUM SOLAR ACTIVITY)

Geometric Altitude (km)	Temp (°K)	Pressure (mb)	Density (gm/cc)	Speed of Sound (m/sec)	Molecular Mass (grams/gram-mole)	Density Scale Height (km)	Number Density (per cc)	Mean Free Path (m)	Viscosity (kg/m sec)
0	534.0	1.67+04	1.65-02	351	44.0	14.21	2.26+20	6.38-09	2.48-05
5	489.2	1.06+04	1.14-02	337	44.0	13.04	1.57+20	9.21-09	2.32-05
10	444.4	6.43+03	7.66-03	322	44.0	11.87	1.05+20	1.38-08	2.13-05
15	399.7	3.71+03	4.91-03	307	44.0	10.69	6.72+19	2.14-08	1.95-05
20	355.1	2.01+03	2.99-03	291	44.0	9.52	4.10+19	3.52-08	1.73-05
25	310.6	1.00+03	1.71-03	274	44.0	8.34	2.34+19	6.17-08	1.53-05
30	273.3	4.51+02	8.73-04	259	44.0	6.15	1.19+19	1.21-07	1.35-05
35	265.0	1.92+02	3.83-04	256	44.0	5.98	5.24+18	2.75-07	1.31-05
40	255.8	7.94+01	1.64-04	252	44.0	5.86	2.25+18	6.41-07	1.27-05
45	244.1	3.17+01	6.87-05	247	44.0	5.65	9.41+17	1.53-06	1.21-05
50	231.1	1.21+01	2.77-05	241	44.0	5.35	3.79+17	3.81-06	1.15-05
55	218.8	4.37+00	1.06-05	236	44.0	5.03	1.45+17	9.97-06	1.10-05
60	207.9	1.50+00	3.81-06	230	44.0	4.78	5.22+16	2.76-05	1.05-05
65	196.8	4.85-01	1.31-06	224	44.0	4.55	1.79+16	8.07-05	1.00-05
70	185.7	1.47-01	4.20-07	218	44.0	4.28	5.75+15	2.51-04	0.92-05
75	176.6	4.19-02	1.26-07	212	44.0	4.02	1.72+15	8.38-04	0.86-05
80	171.1	1.13-02	3.51-08	209	44.0	3.84	4.80+14	3.00-03	0.82-05
85	179.5	3.07-03	9.05-09	214	44.0	3.73	1.24+14	1.16-02	0.88-05
90	203.3	9.35-04	2.43-09	227	44.0	4.03	3.33+13	4.33-02	1.04-05
95	211.4	3.17-04	7.94-10	232	44.0	4.60	1.09+13	1.33-01	1.07-05
100	214.8	1.10-04	2.71-10	234	44.0	4.70	3.72+12	3.88-01	1.08-05
110	265.8	1.57-05	3.13-11	260	44.0	5.06	4.29+11	3.36+00	1.31-05
120	366.6	3.70-06	5.33-12	305	44.0	6.54	7.30+10	1.97+01	1.78-05
130	471.9	1.28-06	1.43-12	334	43.9	8.98	1.96+10	7.36+01	2.24-05
140	542.9	5.34-07	5.18-13	359	43.8	11.15	7.12+09	2.02+02	2.51-05
150	583.8	2.44-07	2.19-13	373	43.6	12.39	3.03+09	4.76+02	2.65-05
160	602.9	1.17-07	1.01-13	375	43.2	13.10	1.40+09	1.03+03	2.71-05
170	612.7	5.77-08	4.81-14	381	42.5	13.72	6.82+08	2.11+03	2.75-05
180	620.3	2.93-08	2.33-14	390	41.1	14.20	3.42+08	4.22+03	2.77-05
190	620.8	1.54-08	1.16-14	402	38.8	14.34	1.80+08	8.02+03	2.77-05
200	621.3	8.53-09	5.76-15	424	34.9	14.55	9.94+07	1.45+04	2.77-05
210	621.5	5.09-09	2.91-15	461	29.5	14.88	5.94+07	2.43+04	2.78-05
220	621.7	3.36-09	1.49-15	523	22.9	15.41	3.91+07	3.68+04	2.78-05
230	621.8	2.46-09	7.85-16	617	16.5	16.31	2.87+07	5.03+04	2.78-05
240	622.0	1.98-09	4.32-16	746	11.3	17.88	2.31+07	6.24+04	2.78-05
250	622.1	1.71-09	2.55-16	903	7.7	20.70	1.99+07	7.23+04	2.78-05
260	622.3	1.55-09	1.64-16	1069	5.5	25.76	1.80+07	8.01+04	2.78-05
270	622.4	1.43-09	1.17-16	1220	4.2	34.59	1.67+07	8.63+04	2.78-05
280	622.6	1.35-09	9.18-17	1336	3.5	49.19	1.57+07	9.16+04	2.78-05

*A one- or two-digit number (preceded by a plus or minus sign) following an entry indicates the power of ten by which that entry should be multiplied.

TABLE VII*

1968 VENUS MODEL ATMOSPHERE, V-3

(HIGH DENSITY AND MEAN SOLAR ACTIVITY)

Geometric Altitude (km)	Temp (°K)	Pressure (mb)	Density (gm/cc)	Speed of Sound (m/sec)	Molecular Mass (grams/gram-mole)	Density Scale Height (km)	Number Density (per cc)	Mean Free Path (m)	Viscosity (kg/m sec)
0	770.0	1.69+05	1.12-01	412	42.4	20.29	1.59+21	9.18-10	3.26-05
5	733.3	1.25+05	8.71-02	411	42.4	19.35	1.24+21	1.18-09	3.16-05
10	696.6	9.13+04	6.68-02	405	42.4	18.42	9.49+20	1.54-09	3.05-05
15	660.0	6.54+04	5.06-02	395	42.4	17.48	7.18+20	2.03-09	2.93-05
20	619.9	4.60+04	3.79-02	384	42.4	16.76	5.38+20	2.72-09	2.79-05
25	579.9	3.16+04	2.78-02	372	42.4	15.71	3.95+20	3.70-09	2.65-05
30	540.0	2.12+04	2.00-02	360	42.4	14.65	2.84+20	5.14-09	2.52-05
35	494.1	1.37+04	1.42-02	346	42.4	13.88	2.01+20	7.26-09	2.36-05
40	448.3	8.54+03	9.72-03	331	42.4	12.62	1.38+20	1.06-08	2.17-05
45	402.6	5.05+03	6.40-03	315	42.4	11.35	9.09+19	1.61-08	1.98-05
50	357.0	2.81+03	4.01-03	298	42.4	10.08	5.70+19	2.57-08	1.76-05
55	311.4	1.44+03	2.36-03	280	42.4	8.81	3.35+19	4.36-08	1.56-05
60	273.3	6.68+02	1.25-03	264	42.4	6.40	1.77+19	8.26-08	1.37-05
65	265.4	2.93+02	5.63-04	261	42.4	6.20	8.00+18	1.83-07	1.34-05
70	256.2	1.25+02	2.50-04	257	42.4	6.07	8.55+18	4.12-07	1.29-05
75	244.3	5.19+01	1.08-04	252	42.4	5.87	1.54+18	9.50-07	1.24-05
80	231.2	2.05+01	4.52-05	246	42.4	5.59	6.42+17	2.28-06	1.18-05
85	218.8	7.69+00	1.79-05	241	42.4	5.24	2.55+17	5.74-06	1.12-05
90	208.3	2.75+00	6.72-06	235	42.4	4.98	9.55+16	1.53-05	1.08-05
95	197.2	9.29-01	2.40-06	198	42.4	4.74	3.41+16	4.28-05	1.02-05
100	185.8	2.95-01	8.10-07	192	42.4	4.47	1.15+16	1.27-04	0.94-05
110	171.0	2.50-02	7.45-08	184	42.4	3.98	1.06+15	1.38-03	0.85-05
120	203.9	2.24-03	5.61-09	232	42.4	4.25	7.97+13	1.83-02	1.06-05
130	211.4	2.87-04	6.92-10	237	42.4	4.77	9.84+12	1.49-01	1.09-05
140	263.2	4.33-05	8.39-11	264	42.4	5.03	1.19+12	1.23+00	1.32-05
150	378.3	1.09-05	1.46-11	318	42.4	6.63	2.08+11	7.02+00	1.87-05
160	502.4	4.14-06	4.10-12	357	42.4	9.43	5.97+10	2.45+01	2.39-05
170	589.9	1.91-06	1.63-12	385	41.8	12.30	2.34+10	6.29+01	2.69-05
180	638.2	9.62-07	7.49-13	397	41.8	13.45	1.09+10	1.35+02	2.85-05
190	670.9	5.14-07	3.72-13	411	40.6	15.04	5.55+09	2.65+02	2.96-05
200	690.6	2.85-07	1.97-13	421	39.7	16.31	2.99+09	4.93+02	3.02-05
210	700.6	1.62-07	1.08-13	430	38.7	16.86	1.68+09	8.78+02	3.06-05
220	704.9	9.46-08	6.05-14	438	37.5	17.61	9.72+08	1.52+03	3.07-05
230	707.7	5.64-08	3.46-14	447	36.2	18.27	5.77+08	2.56+03	3.08-05
240	708.9	3.43-08	2.02-14	457	34.7	18.87	3.51+08	4.20+03	3.08-05
250	709.3	2.14-08	1.20-14	468	33.0	19.61	2.19+08	6.73+03	3.08-05
260	709.5	1.37-08	7.28-15	481	31.3	20.42	1.40+08	1.05+04	3.08-05
270	709.7	9.02-09	4.51-15	495	29.5	21.36	9.21+07	1.60+04	3.08-05
280	709.9	6.09-09	2.85-15	512	27.7	22.44	6.21+07	2.37+04	3.08-05
290	710.2	4.22-09	1.85-15	529	25.9	23.66	4.30+07	3.42+04	3.09-05
300	710.4	3.00-09	1.22-15	548	24.1	25.01	3.06+07	4.82+04	3.09-05
310	710.6	2.18-09	8.30-16	568	22.4	26.48	2.23+07	6.62+04	3.09-05
320	710.8	1.63-09	5.75-16	589	20.9	28.06	1.66+07	8.88+04	3.09-05
330	711.0	1.24-09	4.06-16	612	19.4	29.72	1.26+07	1.17+05	3.09-05
340	711.2	9.64-10	2.93-16	635	18.0	31.46	9.82+06	1.50+05	3.09-05
350	711.5	7.65-10	2.15-16	661	16.6	33.24	7.78+06	1.89+05	3.09-05
360	711.7	6.17-10	1.60-16	687	15.4	35.08	6.28+06	2.35+05	3.09-05
370	711.9	5.07-10	1.21-16	716	14.2	36.96	5.16+06	2.86+05	3.09-05
380	712.1	4.23-10	9.32-17	746	13.0	38.89	4.30+06	3.43+05	3.09-05

*A one- to two-digit number (preceded by a plus or minus sign) following an entry indicates the power of ten by which that entry should be multiplied.

TABLE VIII*

1968 VENUS MODEL ATMOSPHERE, V-4

(LOW DENSITY AND MEAN SOLAR ACTIVITY)

Geometric Altitude (km)	Temp (°K)	Pressure (mb)	Density (gm/cc)	Speed of Sound (m/sec)	Molecular Mass (grams/gram-mole)	Density Scale Height (km)	Number Density (per cc)	Mean Free Path (m)	Viscosity (kg/m sec)
0	534.0	1.67+04	1.65-02	351	44.0	14.21	2.26+20	6.38-09	2.48-05
5	489.2	1.06+04	1.14-02	337	44.0	13.04	1.57+20	9.21-09	2.32-05
10	444.4	6.43+03	7.66-03	322	44.0	11.87	1.05+20	1.38-08	2.13-05
15	399.7	3.71+03	4.91-03	307	44.0	10.69	6.72+19	2.14-08	1.95-05
20	355.1	2.01+03	2.99-03	291	44.0	9.52	4.10+19	3.52-08	1.73-05
25	310.6	1.00+03	1.71-03	274	44.0	8.34	2.34+19	6.17-08	1.53-05
30	273.3	4.51+02	8.73-04	259	44.0	6.15	1.19+19	1.21-07	1.35-05
35	265.4	1.92+02	3.82-04	256	44.0	5.97	5.23+18	2.75-07	1.31-05
40	256.2	7.95+01	1.64-04	252	44.0	5.84	2.25+18	6.42-07	1.27-05
45	244.3	3.18+01	6.89-05	247	44.0	5.65	9.43+17	1.53-06	1.21-05
50	231.2	1.21+01	2.78-05	241	44.0	5.37	3.80+17	3.79-06	1.15-05
55	218.8	4.38+00	1.06-05	236	44.0	5.04	1.45+17	9.93-06	1.10-05
60	208.3	1.50+00	3.82-06	230	44.0	4.79	5.23+16	2.75-05	1.06-05
65	197.2	4.89-01	1.31-06	224	44.0	4.56	1.80+16	8.03-05	1.00-05
70	185.8	1.49-01	4.24-07	218	44.0	4.30	5.80+15	2.49-04	0.92-05
75	176.6	4.24-02	1.27-07	212	44.0	4.04	1.74+15	8.29-04	0.86-05
80	171.0	1.15-02	3.55-08	209	44.0	3.84	4.86+14	2.97-03	0.82-05
85	177.9	3.08-03	9.15-09	213	44.0	3.58	1.25+14	1.15-02	0.87-05
90	203.9	9.39-04	2.44-09	228	44.0	4.11	3.34+13	4.32-02	1.04-05
95	213.3	3.22-04	7.99-10	233	44.0	4.76	1.09+13	1.32-01	1.08-05
100	211.4	1.11-04	2.78-10	232	44.0	4.60	3.81+12	3.78-01	1.07-05
110	263.2	1.56-05	3.14-11	259	44.0	4.87	4.30+11	3.36+00	1.30-05
120	378.4	3.71-06	5.19-12	310	44.0	6.47	7.11+10	2.03+01	1.84-05
130	502.4	1.35-06	1.42-12	345	43.9	9.12	1.95+10	7.39+01	2.37-05
140	591.0	6.02-07	5.37-13	375	43.8	11.58	7.38+09	1.95+02	2.67-05
150	641.4	2.95-07	2.41-13	385	43.7	13.34	3.33+09	4.33+02	2.84-05
160	674.9	1.52-07	1.17-13	396	43.4	14.65	1.63+09	8.86+02	2.96-05
170	691.5	8.05-08	6.01-14	403	42.9	15.31	8.44+08	1.71+03	3.01-05
180	700.8	4.38-08	3.16-14	410	42.0	15.75	4.52+08	3.19+03	3.04-05
190	705.5	2.44-08	1.69-14	419	40.6	16.13	2.50+08	5.76+03	3.06-05
200	707.8	1.40-08	9.10-15	432	38.3	16.37	1.43+08	1.01+04	3.06-05
210	709.0	8.37-09	4.95-15	453	34.8	16.63	8.56+07	1.68+04	3.07-05
220	709.4	5.32-09	2.72-15	487	30.1	16.98	5.43+07	2.65+04	3.07-05
230	709.4	3.64-09	1.51-15	540	24.5	17.46	3.72+07	3.88+04	3.07-05
240	709.5	2.70-09	8.57-16	618	18.7	18.22	2.76+07	5.23+04	3.07-05
250	709.6	2.16-09	5.00-16	725	13.6	19.45	2.21+07	6.52+04	3.07-05
260	709.7	1.85-09	3.04-16	858	9.7	21.49	1.88+07	7.65+04	3.07-05
270	709.8	1.65-09	1.96-16	1010	7.0	24.89	1.68+07	8.57+04	3.07-05
280	709.8	1.52-09	1.36-16	1163	5.3	30.54	1.55+07	9.31+04	3.07-05
290	709.9	1.42-09	1.02-16	1302	4.2	39.68	1.45+07	9.93+04	3.07-05

*A one- and two-digit number (preceded by a plus or minus sign) following an entry indicates the power of ten by which that entry should be multiplied.

TABLE IX*

1968 VENUS MODEL ATMOSPHERE, V-5

(HIGH DENSITY AND MAXIMUM SOLAR ACTIVITY)

Geometric Altitude (km)	Temp (°K)	Pressure (mb)	Density (gm/cc)	Speed of Sound (m/sec)	Molecular Mass (grams/ gram-mole)	Density Scale Height (km)	Number Density (per cc)	Mean Free Path (m)	Viscosity (kg/m sec)
0	770.0	1.69+05	1.12-01	412	42.4	20.29	1.59+21	9.18-10	3.26-05
5	733.3	1.25+05	8.71-02	411	42.4	19.35	1.24+21	1.19-09	3.16-05
10	696.6	9.13+04	6.68-02	405	42.4	18.42	9.49+20	1.54-09	3.05-05
15	660.0	6.54+04	5.06-02	395	42.4	17.48	7.18+20	2.03-09	2.93-05
20	619.9	4.60+04	3.79-02	384	42.4	16.76	5.38+20	2.72-09	2.79-05
25	579.9	3.16+04	2.78-02	372	42.4	15.71	3.95+20	3.70-09	2.65-05
30	540.0	2.12+04	2.00-02	360	42.4	14.65	2.84+20	5.15-09	2.52-05
35	494.1	1.37+04	1.42-02	346	42.4	13.88	2.01+20	7.26-09	2.36-05
40	448.3	8.54+03	9.72-03	331	42.4	12.62	1.38+20	1.06-08	2.17-05
45	402.6	5.05+03	6.40-03	315	42.4	11.35	9.09+19	1.61-08	1.98-05
50	357.0	2.81+03	4.01-03	298	42.4	10.08	5.70+19	2.57-08	1.76-05
55	311.4	1.44+03	2.36-03	280	42.4	8.81	5.35+19	4.36-08	1.56-05
60	273.3	6.68+02	1.25-03	264	42.4	6.40	1.77+19	8.26-08	1.37-05
65	265.2	2.93+02	5.63-04	261	42.4	6.21	8.00+18	1.83-07	1.33-05
70	256.3	1.25+02	2.50-04	257	42.4	6.10	3.55+18	4.12-07	1.29-05
75	244.6	5.19+01	1.08-04	252	42.4	5.88	1.54+18	9.51-07	1.24-05
80	231.7	2.05+01	4.52-05	246	42.4	5.57	6.42+17	2.28-06	1.18-05
85	219.6	7.73+00	1.79-05	241	42.4	5.24	2.55+17	5.74-06	1.13-05
90	208.9	2.77+00	6.75-06	235	42.4	5.00	9.59+16	1.52-05	1.08-05
95	197.9	9.40-01	2.42-06	198	42.4	4.75	3.44+16	4.25-05	1.02-05
100	187.0	3.00-01	8.19-07	193	42.4	4.48	1.16+16	1.26-04	0.95-05
110	172.5	2.59-02	7.65-08	185	42.4	4.02	1.09+15	1.35-03	0.85-05
120	203.0	2.36-03	5.92-09	232	42.4	4.17	8.41+13	1.74-02	1.05-05
130	216.7	3.03-04	7.14-10	240	42.4	4.90	1.01+13	1.44-01	1.11-05
140	272.3	4.76-05	8.91-11	269	42.4	5.25	1.27+12	1.15+00	1.37-05
150	399.3	1.26-05	1.59-11	326	42.4	6.82	2.28+11	6.41+00	1.97-05
160	555.8	5.12-06	4.60-12	375	42.4	9.55	6.67+10	2.19+01	2.57-05
170	675.4	2.57-06	1.91-12	406	41.8	12.45	2.75+10	5.35+01	2.97-05
180	760.0	1.43-06	9.40-13	432	41.5	15.19	1.36+10	1.08+02	3.23-05
190	826.0	8.50-07	5.07-13	450	40.9	17.99	7.46+09	1.98+02	3.42-05
200	862.3	5.25-07	2.95-13	463	40.3	19.01	4.41+09	3.34+02	3.52-05
210	890.2	3.33-07	1.78-13	474	39.6	20.82	2.71+09	5.44+02	3.60-05
220	905.9	2.15-07	1.11-13	483	38.9	21.51	1.72+09	8.56+02	3.65-05
230	916.7	1.42-07	7.07-14	492	38.0	22.65	1.12+09	1.32+03	3.68-05
240	922.8	9.46-08	4.57-14	500	37.1	23.24	7.43+08	1.98+03	3.69-05
250	926.8	6.41-08	2.99-14	508	36.0	24.09	5.01+08	2.94+03	3.71-05
260	928.9	4.40-08	1.99-14	517	34.9	24.72	3.43+08	4.29+03	3.71-05
270	930.1	3.07-08	1.33-14	526	33.7	25.54	2.39+08	6.17+03	3.71-05
280	930.5	2.17-08	9.07-15	537	32.4	26.31	1.69+08	8.73+03	3.72-05
290	930.9	1.56-08	6.24-15	548	31.0	27.17	1.21+08	1.22+04	3.72-05
300	931.3	1.13-08	4.34-15	561	29.7	28.14	8.82+07	1.67+04	3.72-05
310	931.7	8.39-09	3.06-15	574	28.3	29.22	6.52+07	2.26+04	3.72-05
320	932.1	6.30-09	2.19-15	589	26.9	30.40	4.90+07	3.01+04	3.72-05
330	932.5	4.81-09	1.59-15	604	25.6	31.68	3.73+07	3.95+04	3.72-05
340	932.8	3.72-09	1.16-15	621	24.3	33.07	2.89+07	5.10+04	3.72-05
350	933.2	2.92-09	8.66-16	638	23.0	34.55	2.27+07	6.50+04	3.72-05
360	933.6	2.32-09	6.52-16	655	21.8	36.11	1.80+07	8.17+04	3.72-05
370	934.0	1.87-09	4.97-16	674	20.6	37.75	1.45+07	1.01+05	3.73-05
380	934.4	1.53-09	3.84-16	693	19.5	39.45	1.19+07	1.24+05	3.73-05
390	934.8	1.26-09	2.99-16	713	18.4	41.20	9.78+06	1.51+05	3.73-05

*A one- or two-digit number (preceded by a plus or minus sign) following an entry indicates the power of ten by which that entry should be multiplied.

TABLE IX* (CONTINUED)

Geometric Altitude (km)	Temp (°K)	Pressure (mb)	Density (gm/cc)	Speed of Sound (m/sec)	Molecular Mass (grams/gram-mole)	Density Scale Height (km)	Number Density (per cc)	Mean Free Path (m)	Viscosity (kg/m sec)
400	935.1	1.05-09	2.36-16	734	17.4	43.00	8.16+06	1.81+05	3.73-05
410	935.5	8.90-10	1.88-16	755	16.4	44.84	6.89+06	2.14+05	3.73-05
420	935.9	7.58-10	1.51-16	778	15.5	46.71	5.87+06	2.51+05	3.73-05
430	936.3	6.53-10	1.22-16	802	14.6	48.62	5.05+06	2.92+05	3.73-05
440	936.6	5.67-10	1.06-16	827	13.7	50.57	4.39+06	3.36+05	3.73-05
450	937.0	4.97-10	8.23-17	853	12.9	52.56	3.85+06	3.83+05	3.73-05

*A one- or two-digit number (preceded by a plus or minus sign) following an entry indicates the power of ten by which that entry should be multiplied.

TABLE X*

1968 VENUS MODEL ATMOSPHERE, V-6

(LOW DENSITY AND MAXIMUM SOLAR ACTIVITY)

Geometric Altitude (km)	Temp (°K)	Pressure (mb)	Density (gm/cc)	Speed of Sound (m/sec)	Molecular Mass (grams/gram-mole)	Density Scale Height (km)	Number Density (per cc)	Mean Free Path (m)	Viscosity (kg/m sec)
0	534.0	1.67+04	1.65-02	351	44.0	14.21	2.26+20	6.38-09	2.48-05
5	489.2	1.06+04	1.14-02	337	44.0	13.04	1.57+20	9.21-09	2.32-05
10	444.4	6.43+03	7.66-03	322	44.0	11.87	1.05+20	1.38-09	2.13-05
15	399.7	3.71+03	4.91-03	307	44.0	10.69	6.72+19	2.14-08	1.95-05
20	355.1	2.01+03	2.99-03	291	44.0	9.52	4.10+19	3.52-08	1.73-05
25	310.6	1.00+03	1.71-03	274	44.0	8.34	2.34+19	6.17-08	1.53-05
30	273.3	4.51+02	8.73-04	259	44.0	6.15	1.19+19	1.21-07	1.35-05
35	265.2	1.92+02	3.83-04	256	44.0	5.97	5.24+18	2.75-07	1.31-05
40	256.3	7.95+01	1.64-04	252	44.0	5.86	2.25+18	6.42-07	1.27-05
45	244.6	3.18+01	6.88-05	247	44.0	5.66	9.42+17	1.53-06	1.21-05
50	231.7	1.21+01	2.77-05	241	44.0	5.36	3.80+17	3.80-06	1.16-05
55	219.6	4.40+00	1.06-05	236	44.0	5.04	1.45+17	9.92-06	1.10-05
60	208.9	1.52+00	3.84-06	230	44.0	4.80	5.26+16	2.74-05	1.06-05
65	197.9	4.95-01	1.32-06	225	44.0	4.57	1.81+16	7.96-05	1.01-05
70	187.0	1.51-01	4.28-07	218	44.0	4.30	5.86+15	2.46-04	0.93-05
75	178.1	4.35-02	1.29-07	213	44.0	4.05	1.77+15	8.15-04	0.87-05
80	172.5	1.19-02	3.65-08	210	44.0	3.87	4.99+14	2.89-03	0.83-05
85	180.3	3.24-03	9.52-09	214	44.0	3.75	1.30+14	1.11-02	0.88-05
90	203.0	9.88-04	2.58-09	227	44.0	4.04	3.53+13	4.09-02	1.03-05
95	212.4	3.37-04	8.38-10	232	44.0	4.62	1.15+13	1.26-01	1.07-05
100	216.7	1.18-04	2.87-10	235	44.0	4.72	3.93+12	3.66-01	1.09-05
110	272.3	1.72-05	3.35-11	263	44.0	5.09	4.58+11	3.15+00	1.34-05
120	399.3	4.31-06	5.72-12	319	44.0	6.67	7.83+10	1.84+01	1.95-05
130	555.8	1.68-06	1.60-12	363	43.9	9.27	2.19+10	6.59+01	2.55-05
140	675.4	8.14-07	6.36-13	394	43.9	11.97	8.73+09	1.65+02	2.96-05
150	760.0	4.41-07	3.05-13	418	43.8	14.72	4.20+09	3.43+02	3.21-05
160	826.0	2.53-07	1.61-13	433	43.6	17.28	2.22+09	6.49+02	3.40-05
170	862.3	1.51-07	9.15-14	444	43.4	18.11	1.27+09	1.14+03	3.51-05
180	890.2	9.24-08	5.38-14	453	43.1	19.61	7.52+08	1.92+03	3.59-05
190	905.9	5.74-08	3.25-14	459	42.6	20.04	4.59+08	3.14+03	3.64-05
200	916.7	3.63-08	1.99-14	466	41.8	20.81	2.87+08	5.03+03	3.67-05
210	922.8	2.33-08	1.23-14	474	40.7	21.07	1.83+08	7.89+03	3.68-05
220	926.8	1.52-08	7.70-15	485	39.0	21.50	1.19+08	1.21+04	3.70-05
230	928.9	1.02-08	4.84-15	500	36.8	21.73	7.93+07	1.82+04	3.70-05
240	930.1	7.00-09	3.06-15	522	33.8	22.09	5.45+07	2.62+04	3.71-05
250	930.5	5.00-09	1.95-15	553	30.2	22.43	3.89+07	3.70+04	3.71-05
260	930.9	3.73-09	1.25-15	596	26.0	22.89	2.90+07	4.97+04	3.71-05
270	931.3	2.91-09	8.10-16	655	21.6	23.54	2.26+07	6.37+04	3.71-05
280	931.7	2.38-09	5.31-16	730	17.3	24.46	1.85+07	7.80+04	3.71-05
290	932.1	2.03-09	3.55-16	825	13.6	25.79	1.57+07	9.15+04	3.71-05
300	932.5	1.79-09	2.43-16	937	10.5	27.72	1.39+07	1.04+05	3.71-05
310	932.8	1.63-09	1.72-16	1062	8.2	30.57	1.26+07	1.14+05	3.71-05
320	933.2	1.51-09	1.26-16	1194	6.5	34.74	1.17+07	1.23+05	3.71-05
330	933.6	1.42-09	9.66-17	1325	5.3	40.82	1.10+07	1.31+05	3.72-05

*A one- or two-digit number (preceded by a plus or minus sign) following an entry indicates the power of ten by which that entry should be multiplied.

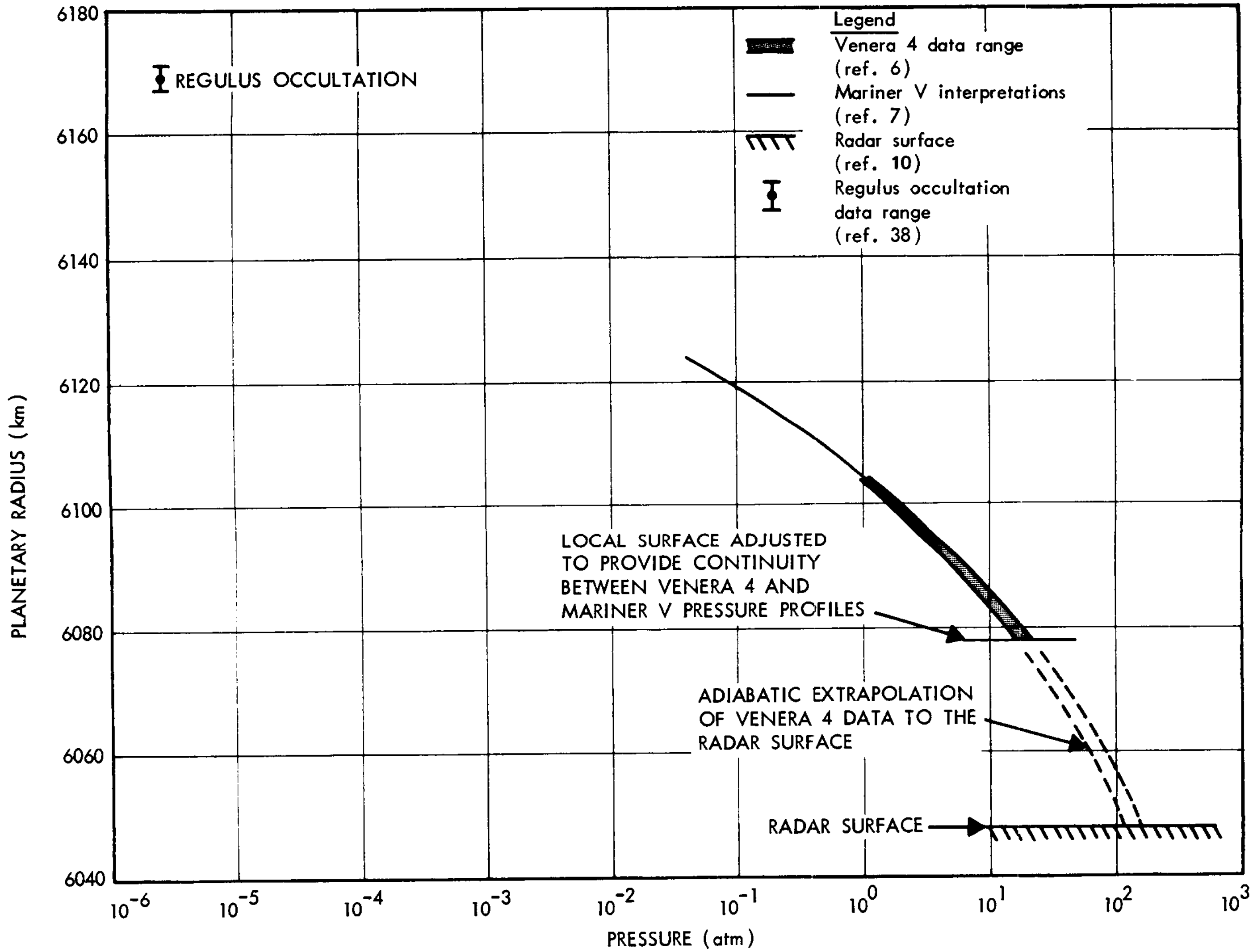

Figure 1. Pressure Data for Venus Atmosphere

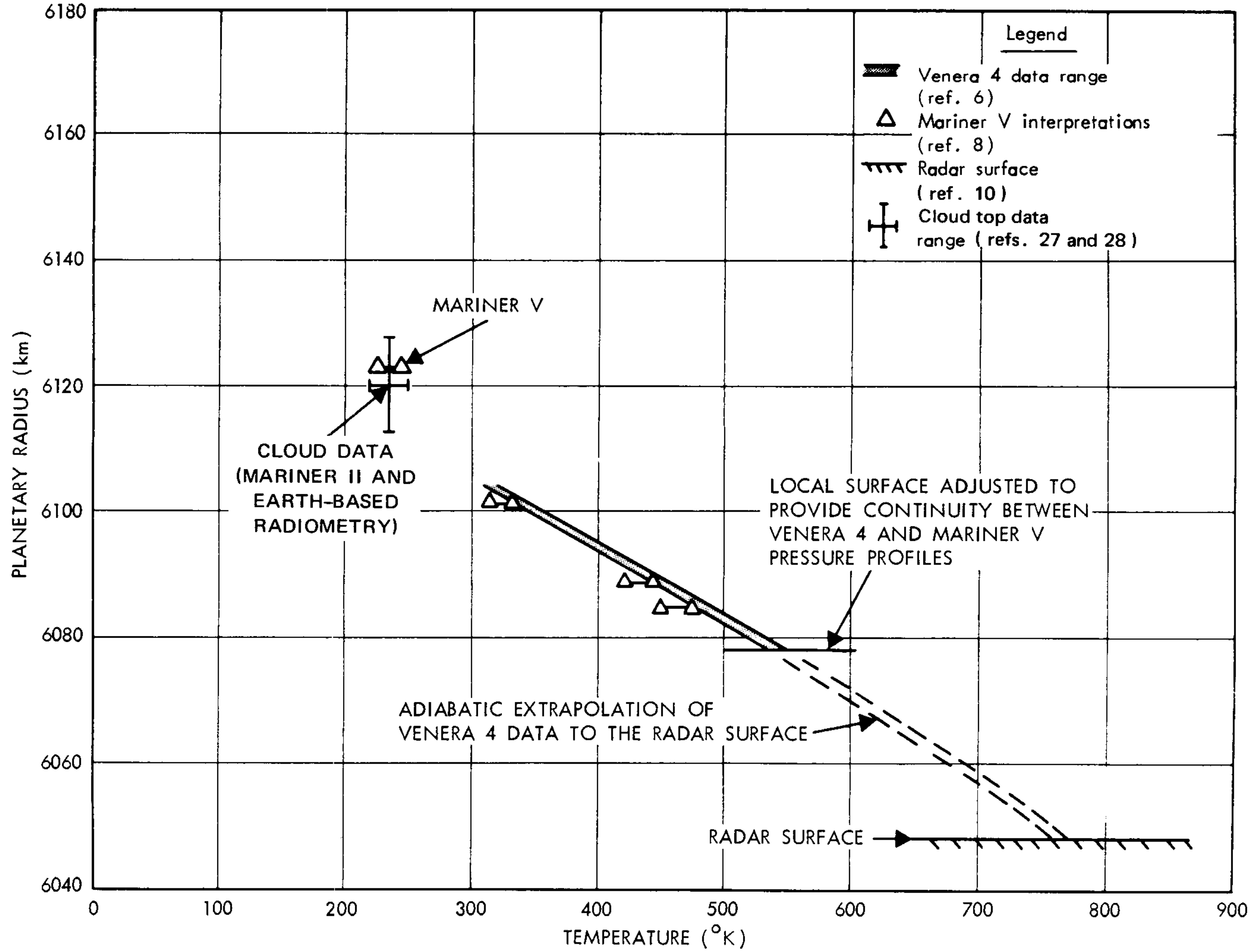

Figure 2. — Temperature Data for Venus Atmosphere

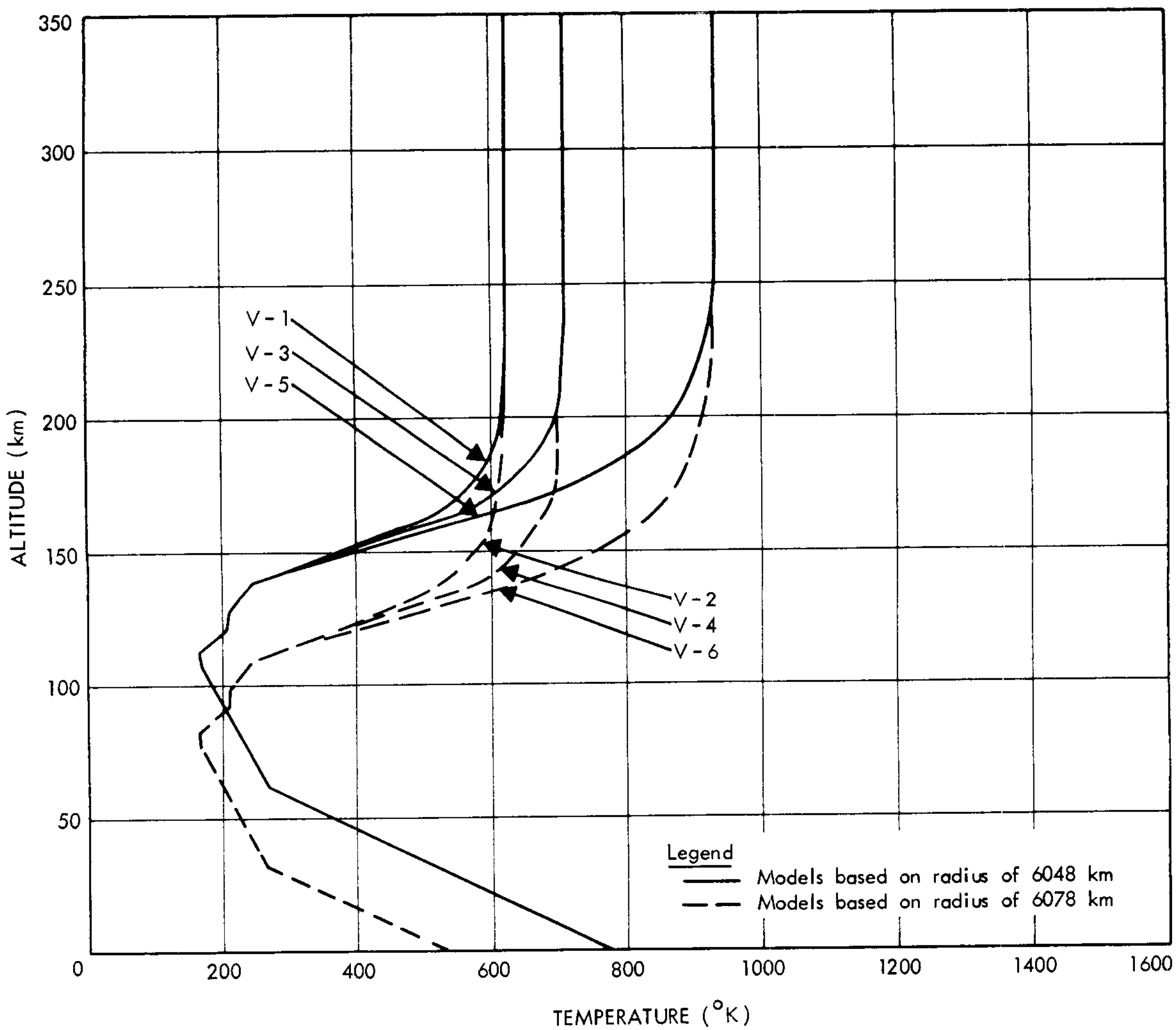

Figure 3. —Temperature vs Altitude for Models of Venus Atmosphere

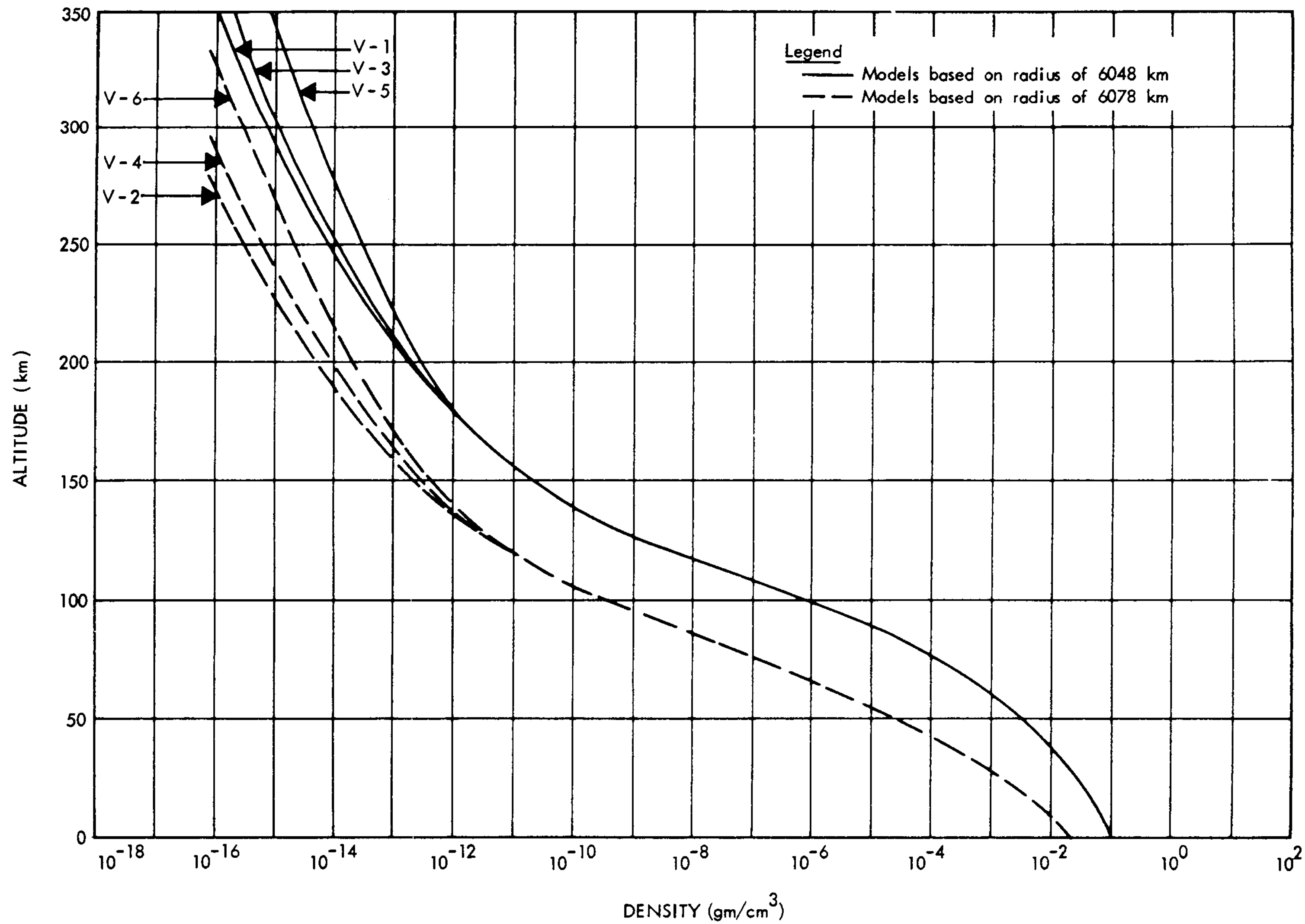

Figure 4. — Density vs Altitude for Models of Venus Atmosphere

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APPENDIX A
List of Symbols

a	speed of sound
C_p	specific heat at constant pressure
C_v	specific heat at constant volume
g	local acceleration of gravity
H_ρ	density scale height
L	mean free path
$M_♀$	mass of Venus
m	molecular mass
n	number density
N	Avogadro's number
p	pressure
r_o	mean planet radius
R	universal gas constant
T	temperature
x	mole fraction of gas
Z	height above the surface
γ	ratio of specific heats (C_p/C_v)
η	viscosity
ν	number of gas components
ρ	density
$\bar{\sigma}$	average effective collision diameter for gas mixture
σ	zero energy collision diameter for a gas
Φ	coefficients for calculating viscosity

$\Omega^{(2,2)*}$ reduced collision integral

SUBSCRIPTS

i,j components i and j of a mixture

mix entire mixture

o denotes surface condition

APPENDIX B

Summary of Method of Computing Model Atmospheres

The results presented in Tables V through X were calculated using the inputs from Table IV and the equations presented here. The calculation of atmosphere parameters was based on a numerical integration of the hydrostatic equation (ref. 35):

$$dp = g\rho dZ$$

The following assumptions were contained within the integration:

(1) Gravity varies as:

$$g = \left(\frac{r_o}{r_o + Z}\right)^2 g_o$$

(2) The gas mixture follows the perfect gas equation of state:

$$\rho = \frac{pm}{RT}$$

(3) The temperature varies with altitude by a series of constant lapse rates.

With p, ρ, and T thus determined as functions of altitude, the following additional quantities may be computed:

Speed of Sound

$$a = \left(\gamma \frac{R}{m} T\right)^{1/2}$$

Density Scale Height

$$H_\rho = \frac{RT/mg}{1 + \frac{R}{g} \frac{d\,(T/m)}{dZ}}$$

Mean Free Path

$$L = \frac{RT}{2^{1/2}\, \pi N \bar{\sigma}^2 p}$$

Viscosity (for the mixture)

$$\eta_{mix} = \sum_{i=1}^{\nu} \frac{\eta_i}{1 + \sum_{\substack{j=1 \\ j \neq i}}^{\nu} \Phi_{i,j} \frac{x_j}{x_i}}$$

where

$$\Phi_{ij} = \frac{\left[1 + \left(\frac{\eta_i}{\eta_j}\right)^{1/2} \left(\frac{m_j}{m_i}\right)^{1/4}\right]^2}{2\sqrt{2}\left(1 + \frac{m_i}{m_j}\right)^{1/2}}$$

$$\eta_i \times 10^6 = 26.693 \frac{\sqrt{mT}}{\sigma^2 \quad \Omega^{(2,2)*}}$$

Number Density $$n = \frac{Np}{RT}$$

APPENDIX C
Glossary

Adiabatic lapse rate. – The rate of change of atmospheric temperature with altitude in the absence of heat transfer, given by $\frac{dT}{dZ} = -g/C_p$, when g is the acceleration of gravity and C_p the specific heat at constant pressure.

Antisolar point. – The point on the planet's surface 180° from the Sun.

Brightness temperature. – The temperature of a black body radiating the same amount of energy per unit area at the wavelengths under consideration as the observed body.

Coriolis parameter. – Twice the component of the planet's angular velocity about the local vertical, $2\,\Omega \sin\phi$, where Ω is the angular velocity and ϕ the latitude.

Spherical (Bond) albedo. – The ratio of the total luminous flux reflected by a planet in all directions to the total flux incident upon it by a beam of parallel light.

Subsolar point. – The point on the planet's surface for which the Sun is at the zenith.

NASA SPACE VEHICLE DESIGN CRITERIA MONOGRAPHS ISSUED TO DATE

SP-8001	(Structures)	Buffeting During Launch and Exit, May 1964
SP-8002	(Structures)	Flight-Loads Measurements During Launch and Exit, December 1964
SP-8003	(Structures)	Flutter, Buzz, and Divergence, July 1964
SP-8004	(Structures)	Panel Flutter, May 1965
SP-8005	(Environment)	Solar Electromagnetic Radiation, June 1965
SP-8006	(Structures)	Local Steady Aerodynamic Loads During Launch and Exit, May 1965
SP-8007	(Structures)	Buckling of Thin-Walled Circular Cylinders, September 1965
SP-8008	(Structures)	Prelaunch Ground Wind Loads, November 1965
SP-8009	(Structures)	Propellent Slosh Loads, August 1968
SP-8010	(Environment)	Models of Mars Atmosphere (1967), May 1968
SP-8014	(Structures)	Entry Thermal Protection, August 1968

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